Report No. CG-D-73-78

LEVEL II

12

FLAME ARRESTOR DESIGN REQUIREMENTS FOR PROLONGED EXPOSURE TO METHANE/AIR, AND GASOLINE/ AIR FLAMES

R. P. WILSON, JR. AND D. P. CROWLEY

AD A063002

FINAL REPORT

SEPTEMBER 1978

D[illegible] nt is available to the public through the [illegible]tional Technical Information Service, Springfield, Virginia 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
Office of Research and Development
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-73-78		

4. Title and Subtitle	5. Report Date
Flame Arrestor Design Requirements for Prolonged Exposure to Methane/Air, Butane/Air [redacted] Gasoline/Air Flames.	September 15, 1978
	6. Performing Organization Code
	8. Performing Organization Report No. 3304.01.03.2
7. Author(s) R. P. Wilson, Jr. [redacted] D. P. CROWLEY	
9. Performing Organization Name and Address Arthur D. Little, Inc. 20 Acorn Park Cambridge, MASS. 02140	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DOT-CG-42,357-A
	13. Type of Report and Period Covered Final Report, G-DSA-1/TP44
12. Sponsoring Agency Name and Address Department of Transportation U. S. Coast Guard (G-DSA-1/TP44) Washington, D. C. 20590	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Tests were performed in order to extend the empirical basis for evaluating the design of flame arrestors to the case of prolonged exposure to a stabilized flame for periods up to 30 minutes. Both parallel plate arrestors and crimped ribbon arrestors, whose dimensions of passageway diameter and length had been shown to be marginal for arresting moving methane/air and butane/air flames were tested. The results of the tests demonstrated that the design criteria (maximum D_j) to withstand prolonged exposure to a stabilized flame are slightly more stringent than the criteria for quenching or arresting a moving flame.

17. Key Words	18. Distribution Statement
Flame Arrestor, Flame Control, Flame Arrestor, Prolonged Flame, Arrestor, Arrester	Document is available to the public through the National Technical Information Service, Springfield, VA. 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	55	

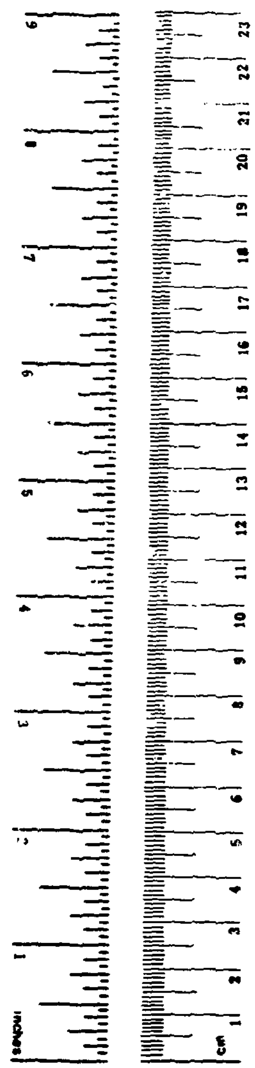
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

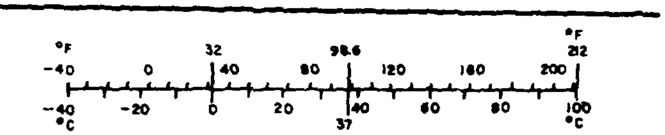


TABLE OF CONTENTS

013

Acknowledgement

Lieutenant Michael Flessner of the Marine Safety Branch, Division of Applied Technology, Office of Research and Development, United States Coast Guard contributed substantially in both the planning and interpretation of the experiments reported herein.

I. BACKGROUND AND SUMMARY OF FINDINGS

A. Background

Tests were performed in order to extend the empirical basis for evaluating the design of flame arrestors to the case of prolonged exposure to a stabilized flame for periods up to 30 minutes. Previous work by Arthur D. Little, Inc. under Contract No. DOT-CG-42357A addressed the design criteria for stopping high-speed flames which can accidentally develop in cargo vent pipes. When flame passage through the arrestor is prevented, the flame does not necessarily extinguish, and in many instances will stabilize at the face of the arrestor where it is supplied with fresh mixture. This situation continues, with gradual heat up of the arrestor and other components in proximity to the flame, until one of three events occur:

(1) The supply of fuel or mixture is shut off by an operator;

(2) The flow rate of mixture is increased until the flame is expelled from the vent piping;

(3) The flame passes through the arrestor, either due to arrestor heat-up or to gross thermal failure (melting of arrestor sections).

The central issue can be stated as follows: Even if the arrestor design is adequate to stop a propagating flame, what additional design constraints must be placed on the arrestor, in order to prevent flame passage during or after heat-up? Two possible criteria come to mind:

(i) The passageway diameter must be smaller if the flame is to be controlled after the arrestor heats up. Basically, the flame speed will increase as the unburned mixture temperature increases and as less heat is lost to the passageway boundary zone because the walls are warmer. The result can be expressed as $D_H^* \sim T_u^{-1/2}$, where D_H^* is the hydraulic diameter of the passageway and T_u is the temperature of the unburned mixture (see reference 4).

(ii) The metal thickness and thermal diffusivity must be adequate to distribute the heat flux received from the flame and to prevent melting. Assuming that arrestor failure occurs whenever the temperature within the arrestor body exceeds some critical value, the arrestor must be designed to keep the bottom portion cool for as long as possible.

In the transient during which a propagating flame attempts to enter the passageways of a flame arrestor, the metal thickness and thermal diffusivity do not affect whether the flame is stopped. (For example, according to tests, plastic arrestors have the same effectiveness as metal arrestors.) This result has been explained by the argument that the flame loses heat to the cold gas next to the walls rather than to the walls themselves. Once the flame stabilizes and begins to heat up the arrestor, the thermal properties of the metal come into play. The interior surfaces of an aluminum arrestor of low mass will reach a greater temperature in steady-state than those of a ceramic or plastic arrestor, and thereby heat up the gas which passes through the arrestor (which favors flame transmission).

Prior work on extended exposure of arrestors has been reported by Bolta et al[1] and Rogowski and Ames.[2] Bolta et al[1] could not induce flashback in 30 minutes through a 1/2-inch thick crimped ribbon arrestor of 0.12 cm crimp height, using propane/air mixtures. This

arrestor was made of stainless steel and reached an equilibrium temperature of 708°F on the hot side within 5 minutes. Doubling the arrestor thickness (to 1-inch) decreased the wall temperature to 477°F but doubled the equilibration time (to 10 minutes). Obviously the flame was stabilized by this thicker arrestor. Doubling the approach speed of the flammable mixture reduced the hot side temperature, as expected.

Rogowski and Ames(2) tested crimped ribbon arrestors of smaller crimp height than Bolta et al (.05 and .10 cm), longer length (1.5 inches), and higher thermal diffusivity (cupro-nickel brass). Since all of these factors assist heat extraction, it was not surprising that Rogowski also found no flame passage for propane/air. However, when tests were performed on ethylene, which has a .15 cm theoretical critical diameter at normal temperature (40% smaller than propane), the arrestor failed after 5-15 minutes. Pyrometer readings of the hot side temperature indicated 1300°K, and (according to the $D_H^* \sim T_u^{-1/2}$ rule of thumb) this temperature would have reduced the flame quenching diameter by a factor of $(1300°K/300°K)^{1/2} = 2.1$, or to .071 cm. Since .071 cm is comparable to the crimp height of the above arrestors, it is not surprising that flame-through occurred.

B. Summary of Findings

1. The parallel plate arrestor , whose dimensions ($L = 0.5"$, $D_H = .045"$) had been shown to be marginal for arresting moving flames (e.g., will arrest low-speed flames but not high-speed flames) did not control stabilized flames during heat-up test using butane/air or gasoline vapor/air for periods longer than approximately one to ten minutes. However, it controlled methane/air flames for periods averaging 25 minutes.

2. The crimped ribbon arrestor, whose dimensions ($L = .375"$, $D_H = .031"$) had been shown to be marginal for arresting moving* methane/air and butane/air flames, failed to control stabilized flames from those same mixtures for periods longer than approximately one to three minutes on the average. However, it successfully controlled flames from gasoline vapor/air for periods of 30 minutes.

3. Based on findings 1 and 2, the design criteria (maximum D_H) to withstand prolonged exposure to a stabilized flame are slightly more stringent than the criteria for quenching or arresting a moving flame.

4. Thermal equilibration occurred for the parallel plate arrestor and crimped ribbon arrestor in 7 minutes and 1 minute, respectively; this response time of course depends on thermal properties (conductivity, heat capacity, thickness of elements, depth of arrestor, etc.). In practical situations, the arrestor heat-up time will be available for mixture shut-off, dilution, steam snuffing or other corrective measures. Therefore the arrestor must be designed to keep the metal temperature in the bottom layer of the arrestor below critical levels as long as possible.

5. Flame passage occurred at the following values of arrestor metal temperature at the center-bottom of the arrestor: $770 \pm 170°F$ for methane/air, $730 \pm 100°F$ for gasoline vapor/air, and $460 \pm 40°F$ for butane/air. These temperatures and margins encompass the results of Table 3 for both arrestor types.

---

*Flame speeds 2-16 ft/sec.

II. EXPERIMENTAL METHODS

A. Test Facility Description

A complete description of the test facility in which heat-up tests were performed is given in Wilson and Crowley,[3] and is summarized below. No modifications were made to the facility except for the addition of a temperature recording system for monitoring flame arrestor temperatures during tests.

The temperature recording system consisted of a 12-point Leeds and Northrop recorder Model W, several sets of chromel/alumel thermocouples and appropriate feed-through connections.

The flame arrestor apparatus consists of a 6" cylindrical test section, controls and instrumentation. A controlled flow of a specified flammable gas mixture is allowed to pass through the test section (containing the flame arrestor) and is ignited at the start of the test by a spark discharge downstream of the arrestor. The resulting combustion wave accelerates toward the arrestor. For heat-up tests, the fuel/air mixture velocities were adjusted to achieve continuous burning at the arrestor following normal upstream flame propagation. The rate of upstream flame propagation had to be low enough to achieve flame stabilization rather than quenching at the arrestor. Low velocity flame propagation was achieved by operating without an orifice restriction at the test pipe exit (the 18-inch pipe extension was used). The performance of the arrestor was automatically recorded. A photograph and schematic of the apparatus are given in Figures 1 and 2, respectively.

Referring to Figure 2, the test section consists of 6-inch diameter vertical pipe, 17-feet high, with a flame arrestor housing located midway up the pipe. Provisions for both mixture preparation and pressure relief are at the base of the pipe. The actual flame arrestor

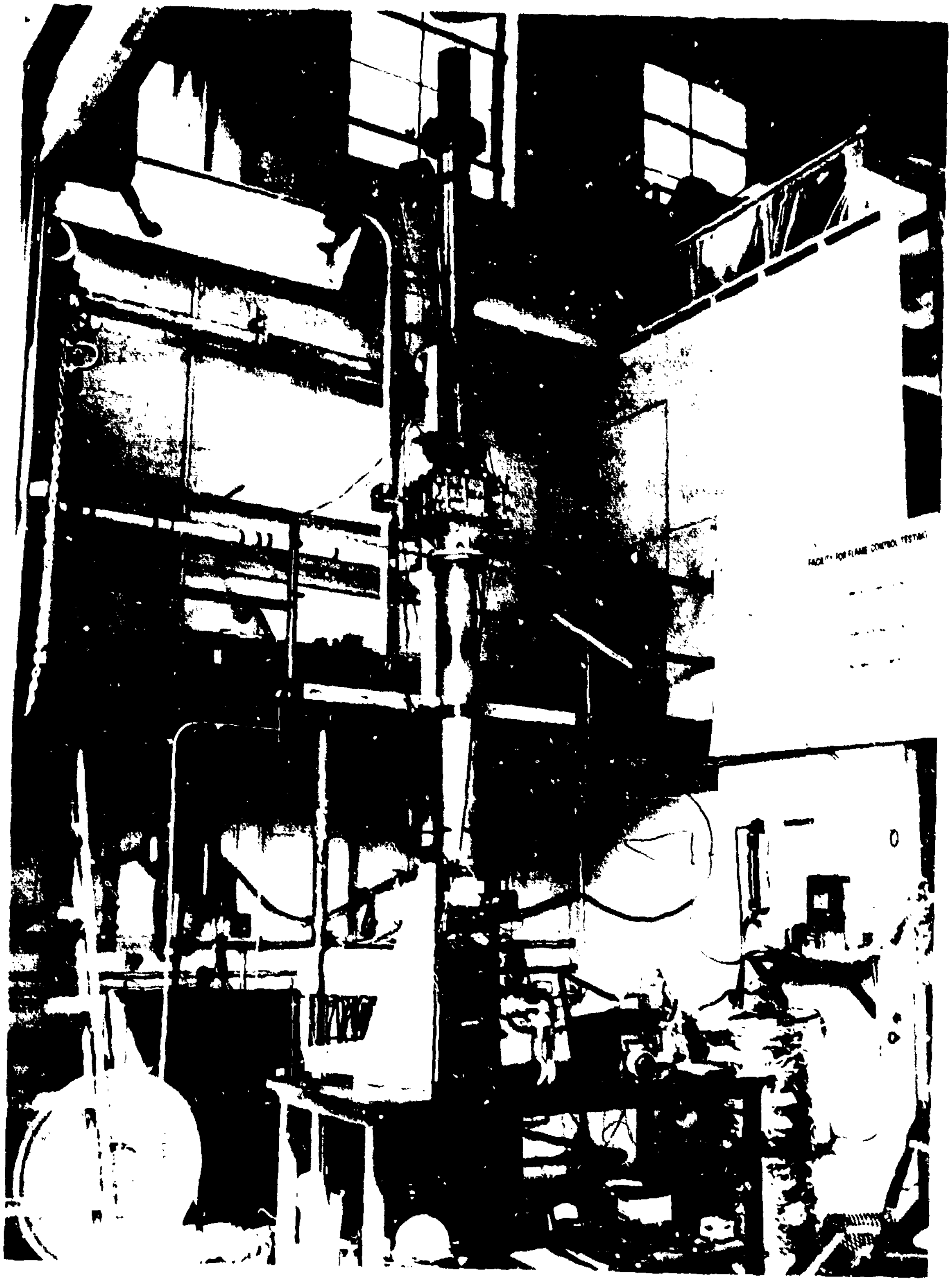


Figure 1: Facility for flame control testing

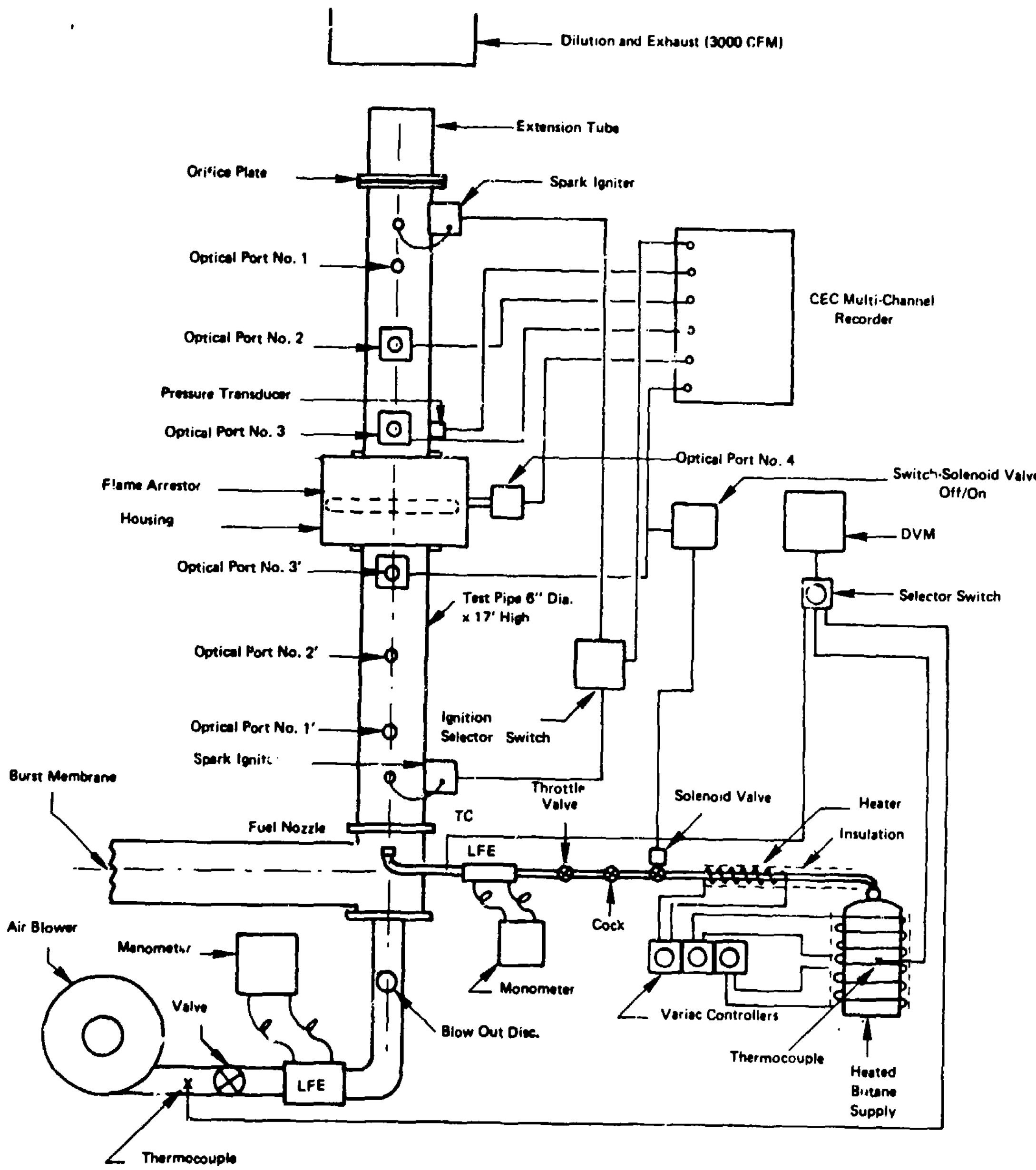


FIGURE 2 FLAME ARRESTOR TEST APPARATUS

device is located midway up the vertical pipe section in the housing shown in Figure 3. It was not necessary to cool the housing despite 30 minute exposures to stabilized flames. For realistic simulation of cargo vent conditions, cooling would not be appropriate in any case. Fuel gas was supplied to the test section through a perforated one-inch diameter capped tube located in the center of the Tee at the base of the test pipe. Tests of concentration decay showed that complete mixing was achieved 1.5 ft above the nozzle.

Butane, methane, and gasoline vapor were used during the program discussed below.

B. Instrumentation

A summary of the instrumentation is given in Table 1. An optical detector at port 3' was used for detection of flame-through at the arrestor. The optical detector in port 3' was also connected via a power amplifier to the fuel solenoid valve. In the event of flame-through, the fuel solenoid would automatically shut off.

In order to measure arrestor temperatures during heat-up tests, thermocouples were installed using a spot welding method at specific locations on each arrestor. The thermocouples were 18" long, 30 gauge chromel/alumel thermocouple wires, electrically insulated using double hole high temperature ceramic tubing.

In the parallel plate arrestors, nine thermocouples were installed in three slots milled out of three arrestor plate elements, as illustrated in Figure 4. The arrangement of the slots was such that temperatures could be measured at three planes (depths) in the arrestor: .062", .25", and .50" from the side of the arrestor facing the flames. After installing the thermocouples in slots, the elements were reassembled in the arrestor and the thermocouples were connected to a Leeds and Northrop multipoint recorder.

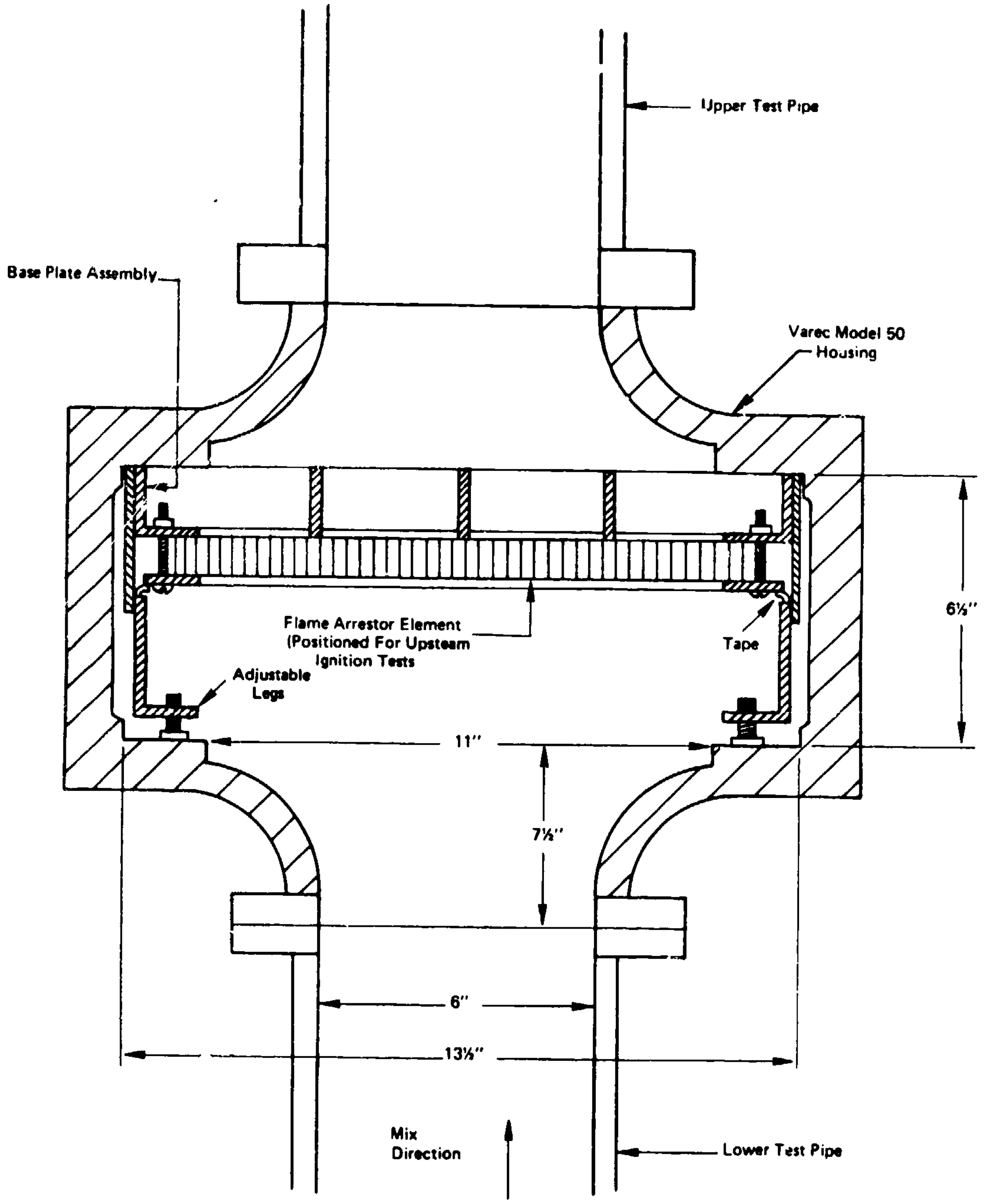
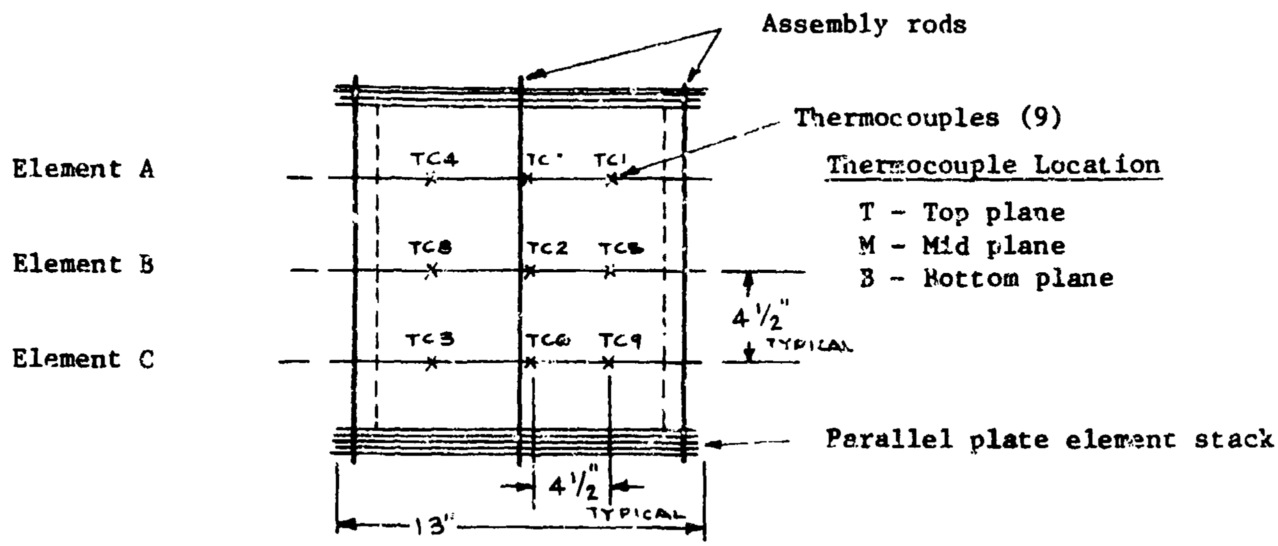


FIGURE 3 HOUSING FOR EXPERIMENTAL FLAME ARRESTORS

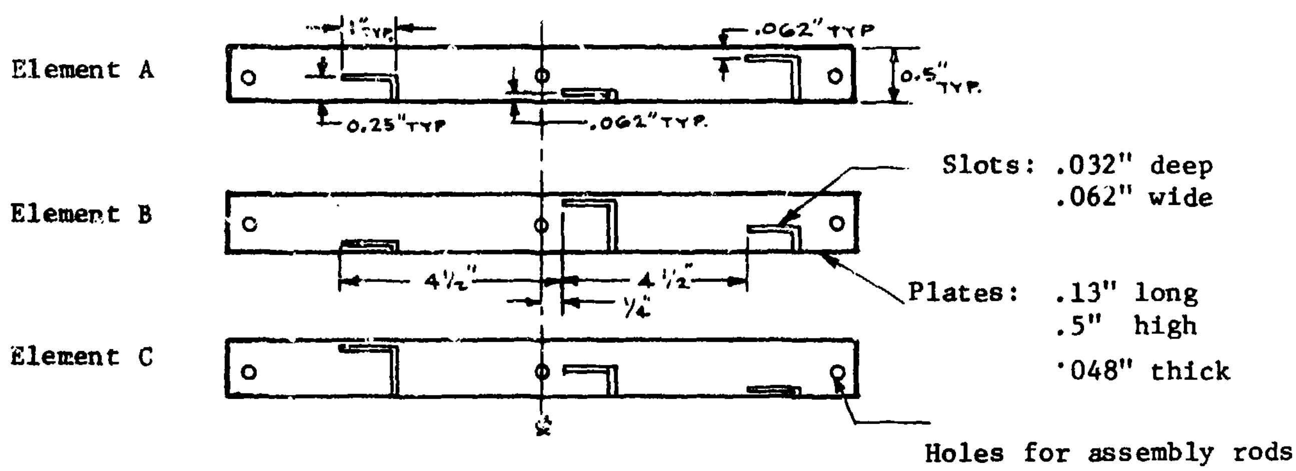
Table 1

Summary of Instrumentation

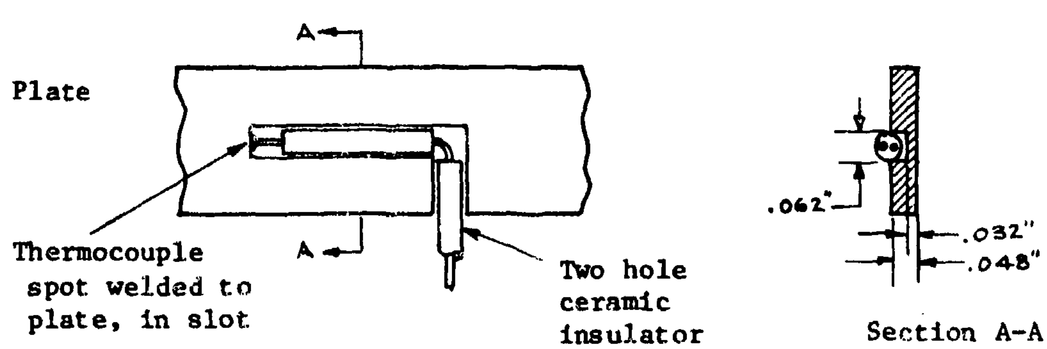
Variables Measured	Measuring Instrument	Accuracy
Air flow rate	Meriam 50 MY 15-4 Flowmeter with Meriam A344 Manometer	± 0.5%
Air temperature	Omega CAIN-116G-24 Thermocouple	± 1°F
Gas flow rate	Meriam 50W201F flowmeter with Ellison IN Manometer	± 0.5%
Gas temperature	Omega CAIN-116G-24 Thermocouple with Dana 4470 Digital Voltmeter	± 1°F
Flame speed	ADL fabricated photodetector system with EG&G HUV 1000 B sensors - 3 units	5% of the value
Flame-through event	ADL fabricated photodetector system with EG&G HUV 1000 B sensor - 1 unit	Positive detection
Test chamber pressure	Kulite XTS-190-200 pressure transducer & ADL fabricated operational circuitry	± 0.5 psi
Spark ignition event Gas Solenoid valve shut off event Photodetector event signals Pressure transducer signals	CEC 5-125 Oscillograph Recorder, 8 channel	Unspecified
Barometric pressure	National weather service - local area	Unspecified
Arrestor Temperatures	Chromel/Alumel thermocouples	± 10°F



Arrestor plan view



Details of thermocouples slot location



Details of thermocouple insulation

Figure 4: Thermocouple Location and Installation Details for Parallel Plate Arrestor

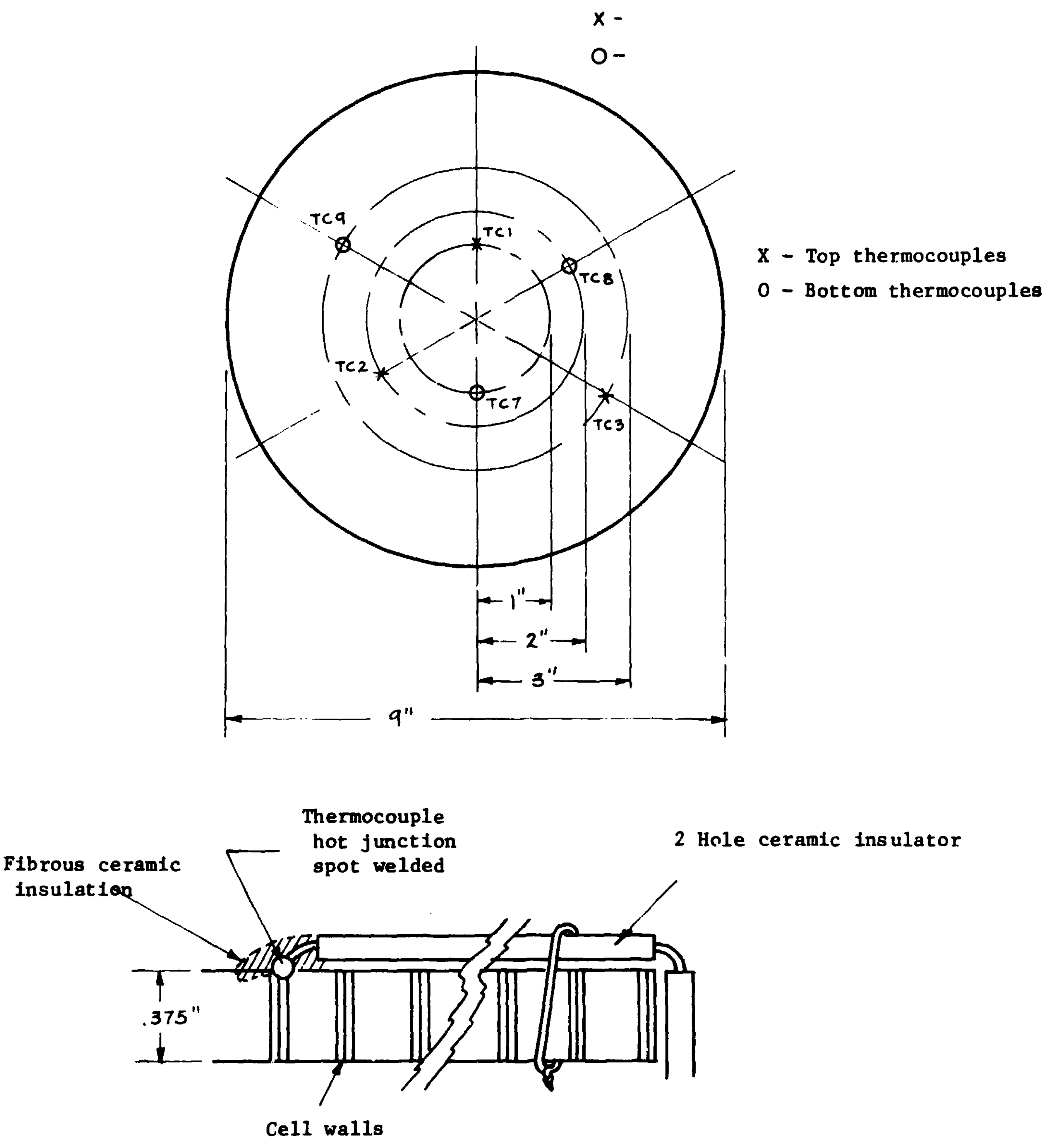
In the crimped ribbon arrestor the thermocouple assemblies were spot welded at the top and bottom surfaces of the arrestor in three radial positions (1", 2", and 3" radius) as illustrated in Figure 5.

An eight channel recorder (CEC Model 5-124) was used to record signals from the instrumentation. The three optical detectors and the pressure detectors were connected directly to the recorder. The signal from the flame-through detector was, as mentioned above, connected to a power amplifier to shut off the fuel solenoid. This signal was also connected to the recorder so that the flame-through event could be recorded. A signal from the ignition switch was also connected to the recorder to record the existence and duration of the spark discharge. During the conduct of heat-up tests, the standard recording system was operated only long enough to record the upstream propagation of the flame front and its stabilization at the arrestor. The multipoint recorder was used for the entire test period, in addition to recording temperature histories, time for flame-through, and top and bottom arrestor temperatures at flame-through were also recorded.

C. <u>Gasoline Vapor Supply System</u>

A system was set up to produce steady state vaporization of gasoline liquid for supplying gasoline vapor to the flame arrestor test apparatus. The system, shown schematically in Figure 6, consisted of a heated packed column containing approximately 1-gallon of liquid gasoline and a heated nitrogen gas supply. The system was designed to saturate a 1 CFM flow of nitrogen with gasoline vapor, producing a vapor mole fraction of about 0.5 depending on nitrogen temperature.

During the 30 minute test duration, the vapor composition varied with time, as discussed in Appendix B. The lighter fractions appeared first, with stabilization after about 5 minutes.



Details of installation method

Figure 5: Thermocouple Location and Installation Methods for Crimped Ribbon Arrestor

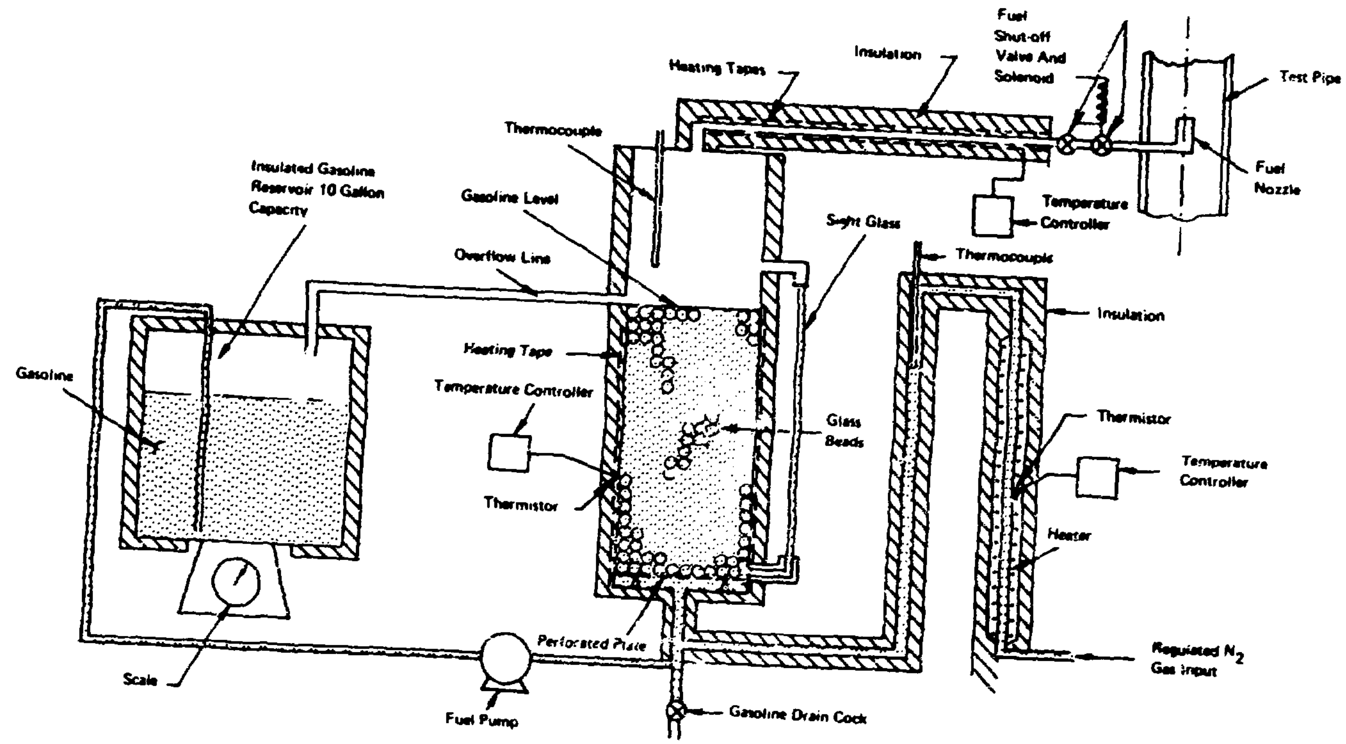


FIGURE 6 GASOLINE VAPOR CONVERTER

D. Operating Procedure

The operating procedure described in reference (3) was modified slightly to permit continuous burning of the gas/air mixtures at the arrestor. The procedure for testing with methane/air and butane/air mixtures differed from that used for testing gasoline/air mixtures.

In conducting tests using methane/air or butane/air mixtures, the following sequential procedure was used:

(1) A safety check of the test site was made which included:

--Access to fire extinguishers;
--Wearing of hard hats, glasses and ear protection;
--Locating danger warnings and restricted area barriers;
--Turning on flashing red lights in critical area of the test site; and
--Turning on the system exhaust fan.

(2) A check of the optical detector and pressure detector battery condition was made.

(3) The main Power Switch was turned on.

(4) The recorder power and optical, pressure detector power, switches were turned on ignition power and DVM power.

(5) The selection of upper ignition source was made.

(6) The arrestor element was installed in the housing and the housing cover secured.

(7) Butane supply and inline heaters were activated and allowed to come to temperature equilibrium (approximately 100°F and 120°F, respectively). For methane, no in-line heaters were used.

(8) The air supply blower was turned on and adjusted to achieve the appropriate flow rate--corrections to the flow rate for barometric pressure and air temperature were made.

(9) Fuel tank valve, fuel shut-off cock and solenoid valve were opened. This was followed by an adjustment of the throttling valve until the appropriate fuel flow rate was achieved. Corrections for barometric pressure and fuel gas temperature were also made.

(10) The gas/air mix was allowed to flow for 60 seconds.

(11) In moderately rapid sequence:

--The multipoint temperature recorder was turned on;

--The high-speed recorder was turned on—(to 1 inch/sec for adequate trace resolution);

--The ignitor was energized—followed immediately by combustion;

--When the passage of the flame front and stabilization of the flame at the arrestor were ascertained from the system recorder trace, the high-speed recorder was shut off. (At this time, optical detectors 2, 3 & 3' were also removed from the test pipe as a precaution against overheating.)

(12) The multipoint recorder was observed for temperature histories of the arrestor elements. Specific note was made of the temperature at which flame-through occurred (if at all). Flame-through was noted both aurally and by the indication of the operation of the automatic fuel shut off valve (triggered by flame-through event).

(13) If flame-through occurred, the air blower was shut off to quench the flame. Otherwise the heat-up test was continued for a period of 30 minutes at which time the manual fuel valve and the air blower was allowed to continue running to assist in the system cool down.

(14) The temperature recorder was shut off and the recording examined for heat-up histories.

For gasoline/air mixtures the procedure was essentially the same as for methane/air and butane/air up to step 6, whereupon the procedure was as follows:

(7) The air blower was turned on and adjusted to achieve the appropriate flow rate.

(8) A five gallon supply of gasoline was placed in the gasoline vapor converter reservoir. (The quantity was sufficient to serve several tests).

(9) The gasoline supply, nitrogen and in-line heaters were activated to achieve an equilibrium temperature of approximately 120°F.

(10) The fuel valve solenoid was opened and the fuel circulation pump was turned on.

(11) After approximately 30 minutes the weight of the gasoline reservoir was measured.

(12) The nitrogen gas valve was opened and adjusted to 3.5 CFM.

(13) After a period of 2 minutes in moderately rapid sequence

--The multipoint temperature recorder was turned on;

--The system recorder was turned on (1 inch/sec);

--The igniter was energized--followed immediately by combustion;

--When the passage of the flame front and flame stabilization at the arrestor were ascertained from the high-speed recorder trace, the recorder was shut off and optical detectors were also removed (as a precaution against overheating).

(14) The temperature recorder was observed for temperature excursions of the arrestor thermocouples.

(15) The heat-up test was allowed to continue for a period up to 30 minutes at which time:

--The temperature recorder was shut off;

--The nitrogen gas was turned off. The air blower was allowed to continue running to assist in system cool down; and

--The fuel valve solenoid was shut off.

(16) The gasoline reservoir was reweighed and an average vaporization rate for the test was determined.

(17) The multipoint recorder was examined to determine temperature histories.

E. Gases Tested

Gases tested during the heat-up tests were as follows:

(1) Methane, C.P., 99.0% minimum purity, gas/air mixture equivalence ratio $\phi \approx 1.1$.

(2) n-Butane, C.P. 99.0% minimum purity, gas/air mixture equivalence ratio $\phi \approx 1.1$.

(3) Gasoline vapor: Mobil Regular, Mobil Regular No Lead, Exxon High Test, evaporated at approximately 120°F through a 22-in high packed column using nitrogen as carrier gas. Approximate vaporization rate 0.4 - 0.6 ft^3/min, gas/air mixture approximately 3 percent by volume. During the 30 minute test period the vapor composition varied with time as discussed in Appendix B.

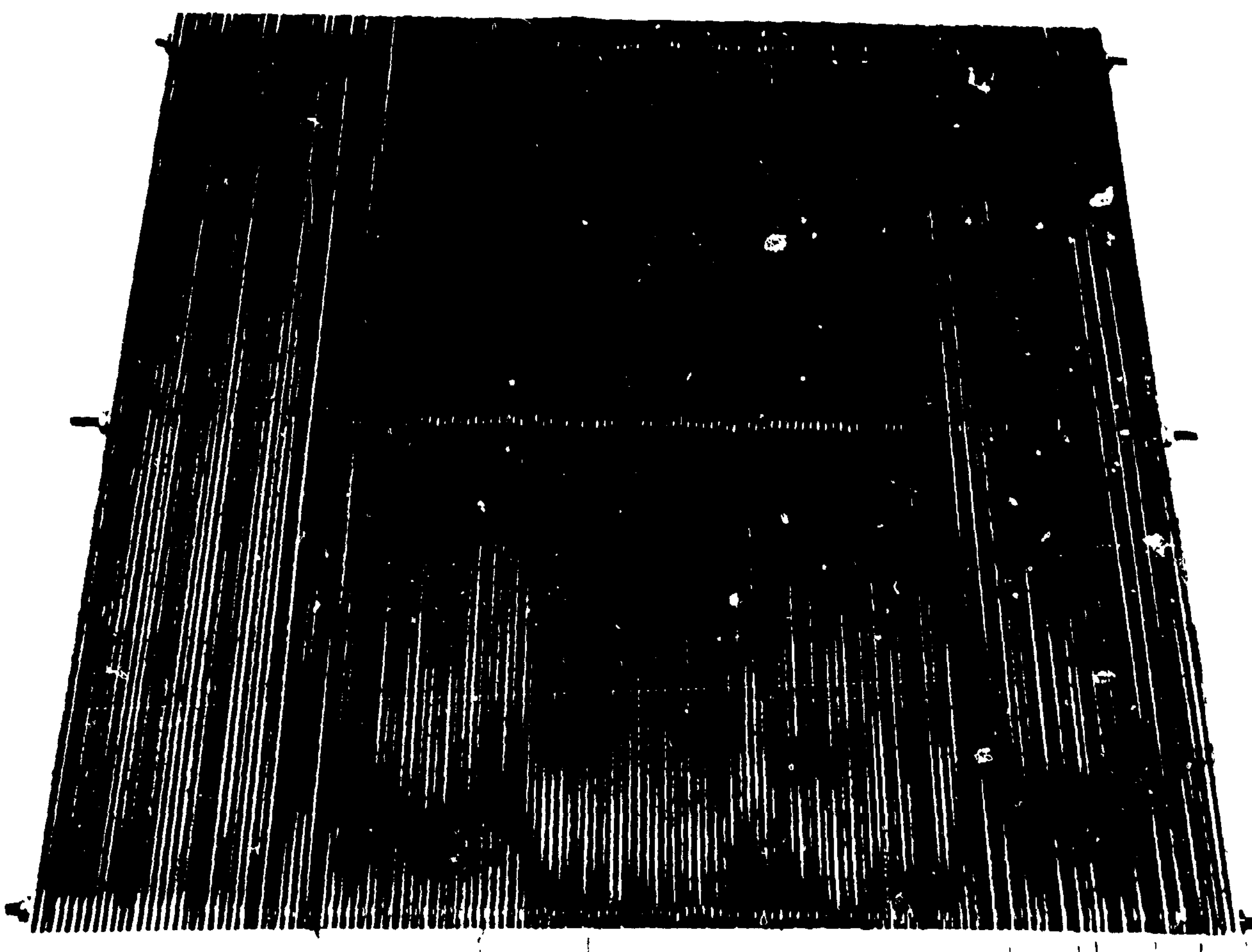
F. Flame Arrestors Tested

Two arrestors were tested for prolonged exposure to flames: a parallel plate arrestor of $L = 0.5$ in, $D_H = 0.045$ in (.032" gap); and a crimped ribbon arrestor of dimensions $L = 0.375$ in, $D_H = 0.035$ in. Table 2 gives detailed dimensions and Figures 7 and 8 display the arrestors.

Table 2

Summary of Flame Arrestors Tested

Type	Figure	Source	Dimensions	L (in)	D_H (in)	L/D_H	Remarks
Parallel Plate	7	Arthur D. Little, Inc. experimental design.	11-1/2" x 11-1/2" x .5", .048" steel plates with .032" gap.	.50	.045	11.1	Extra supports were required to maintain plate parallelity
Crimped Ribbon	8	Arthur D. Little, Inc. experimental design.	9" dia x 0.375" high, half hex crimp, .002" foil x .031" hex height, stainless steel	.375	.035	10.7	-



Arthur D Little Inc

0 1 2 3 4 5
Centimeter Scale

Figure 7: Parallel plate arrestor (.032" gap, 0.5" depth)

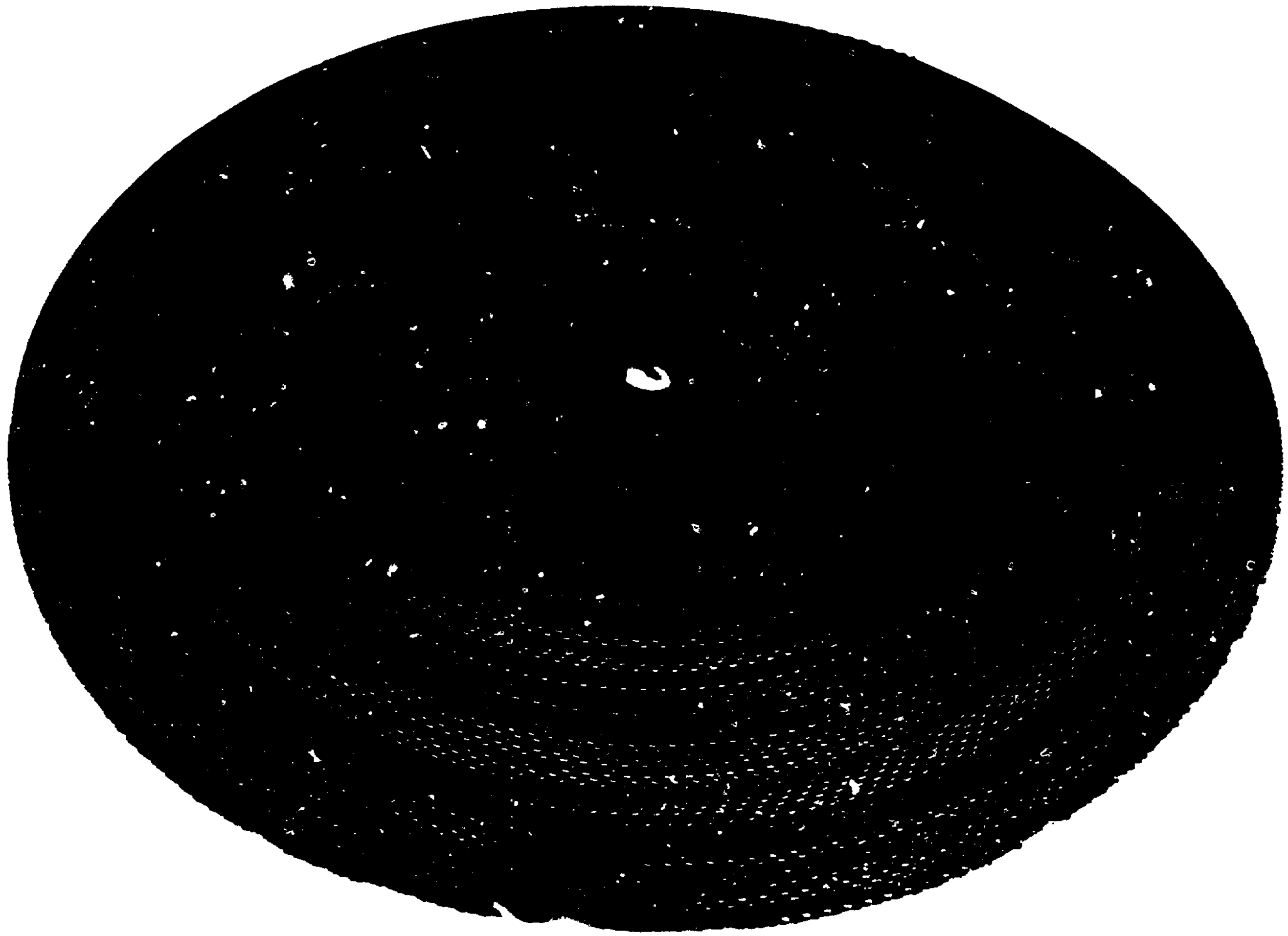


Figure 8: Crimped ribbon arrestor (.031" hex height)

During previous studies (reference 3), these arrestors were found to have marginal dimensions (sufficient to arrest low-speed flames but failing to arrest high-speed flames).

III. PERFORMANCE OF ARRESTORS UNDER PROLONGED FLAME EXPOSURE

A. Results

Except for methane/air mixtures, the parallel plate arrestor failed to control flames during heat-up after periods ranging from approximately one to 10 minutes. The arrestor successfully controlled methane flames for an average of 25 minutes. The crimped ribbon arrestor failed to control methane and butane flames after a period of between approximately one to three minutes. However, the crimped ribbon arrestor successfully controlled gasoline flames for 30 minutes. A summary of the tests results is shown in Table 3. Data from the individual heat-up tests are listed in Table A-1 of Appendix A.

As can be seen from Table 3, the average temperature gradient across the crimped ribbon arrestor was in general significantly higher (by a factor of approximately five) than that of the parallel plate. This is attributed to the difference in thermal properties of the arrestor materials, dimensions of the arrestor elements and heat conduction path of the two arrestors. Table 4 lists dimensions and the estimated thermal properties of the two arrestors.

Figures 9 through 14 illustrate typical time--temperature histories of the top of the arrestors (facing the flame) during the heat-up tests. The figures show histories of the thermocouple that recorded the highest temperature during the tests.

During post-test visual observations of the arrestors, it was noted that the central area (approximately 4" diameter) of the crimped ribbon arrestors appeared to be more heavily oxidized from flame exposure than the remaining (9" diameter) area of the arrestor.

Table 3

SUMMARY OF HEAT-UP TEST RESULTS

ARRESTOR	L	D_H	TEST GAS	FLAME THROUGH YES	FLAME THROUGH NO	AVERAGE TIME TO FLAME THROUGH (min)	AVERAGE TOP TEMP. (°F)	AVERAGE BOTTOM TEMP. (°F)	CENTER BOTTOM TEMP. (°F)	AVERAGE TEMPERATURE GRADIENT $T_{top} - T_{bottom}$ (°F)
Parallel Plate	.5	.045	Methane	X		24.8	1180 ± 50	880 ± 40	950 ± 50	300
Parallel Plate	.5	.045	Butane	X		1.25	420 ± 90	330 ± 70	420 ± 50	90
Parallel Plate	.5	.045	Gasoline: Mobil Lead Free Regular	X		7.7	820 ± 80	680 ± 40		140
Parallel Plate	.5	045	Gasoline: Mobil Regular	X		7.8	820 ± 70	680 ± 70	730 ± 70	140
Parallel Plate	.5	.045	Gasoline: Exxon High Test	X		9.4	820 ± 80	680 ± 80		140
Crimped Ribbon	.375	.035	Methane	X		3.0	1720 ± 920	520 ± 210	600 ± 100	1200
Crimped Ribbon	.375	.035	Butane	X		1.0	1210 ± 750	410 ± 100	510 ± 100	800
Crimped Ribbon	.375	.035	Gasoline: Mobil Lead Free Regular		X	-	(1290 ± 500)*	(610 ± 110)	-	(680)
Crimped Ribbon	.375	.035	Gasoline: Mobil Regular		X	-	(1290 ± 420)*	(660 ± 140)	-	(630)
Crimped Ribbon	.375	.035	Gasoline: Fxxon High Test		X	-	(1590 ± 410)*	(590 ± 170)	-	(1000)

*No flame through for this test

Table 4

Physical and Thermal Properties of Arrestors

Properties	Arrestors	
	Crimped Ribbon	Parallel Plate
Material	Stainless Steel	Cold Rolled Steel
Arrestor Element Thickness (in.)	.002	.048
Arrestor Element Length (in.)	.375	.50
Thermal Conductivity (Btu/hr/ft°F)	8-12	26-36
Specific Heat (Btu/lbm-°F)	.1	.1
Density (lb/in^3)	.28	.28

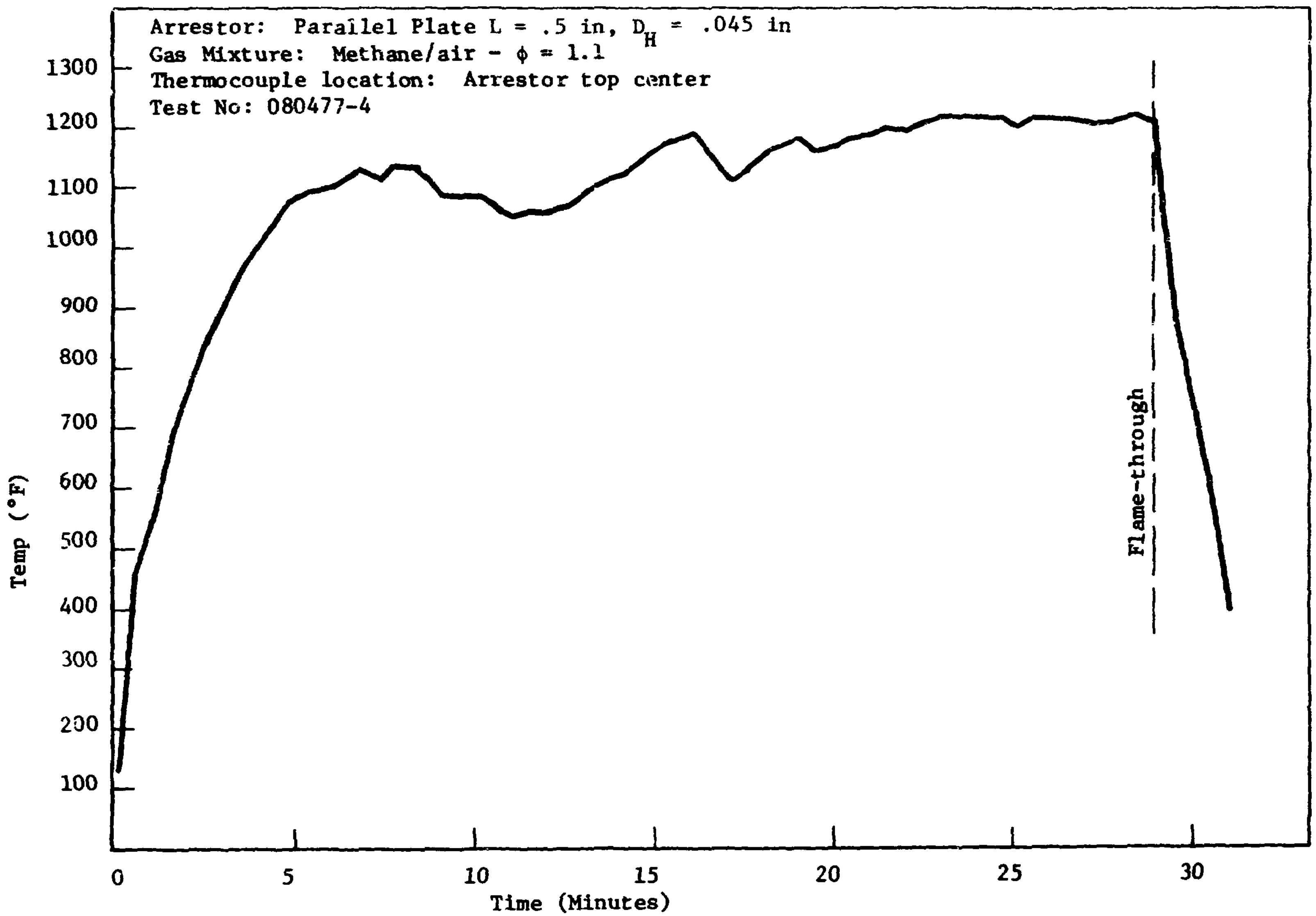


Figure 9: Temperature History During Heat-Up

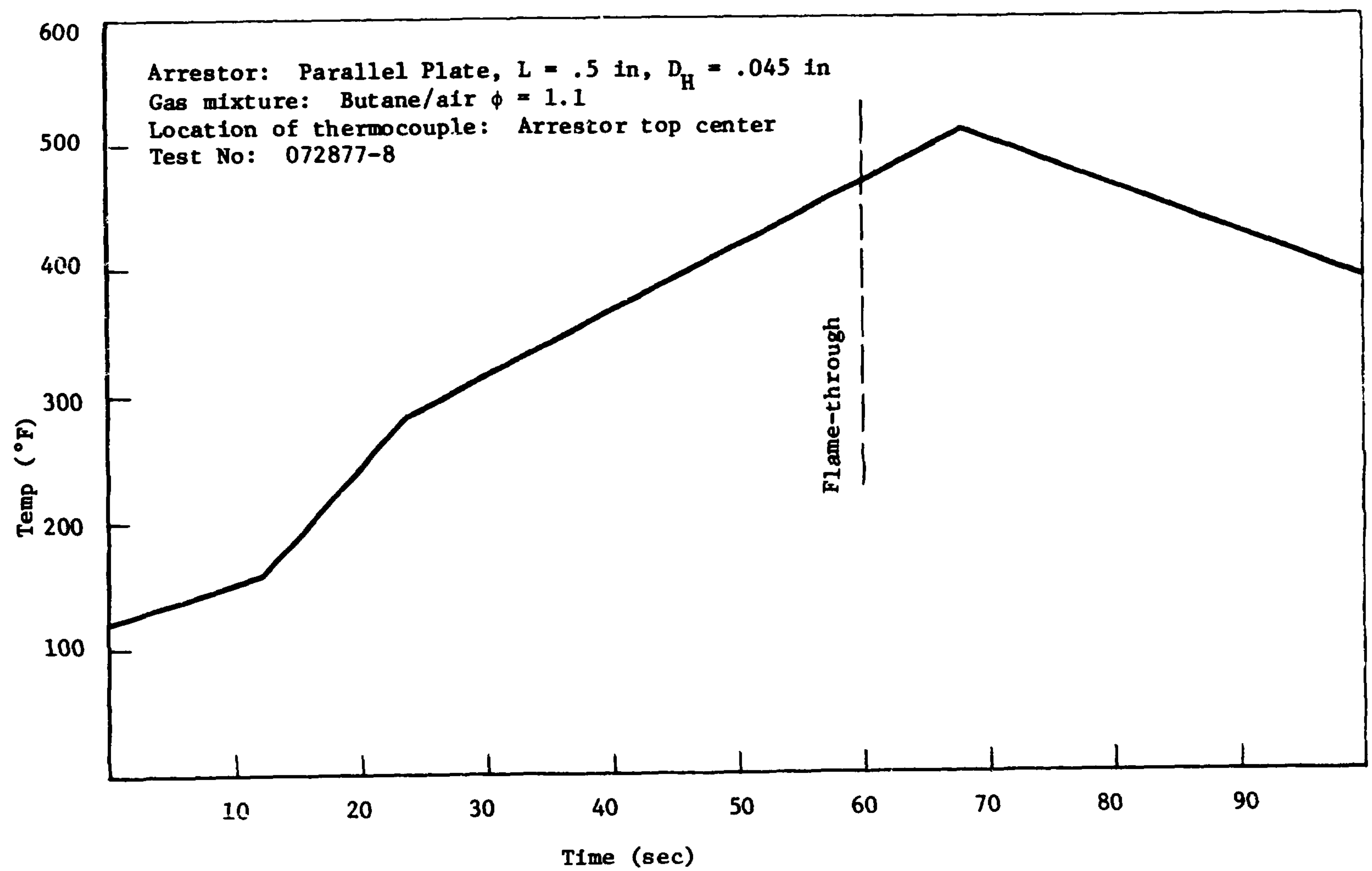


Figure 10: Temperature History During Heat-Up

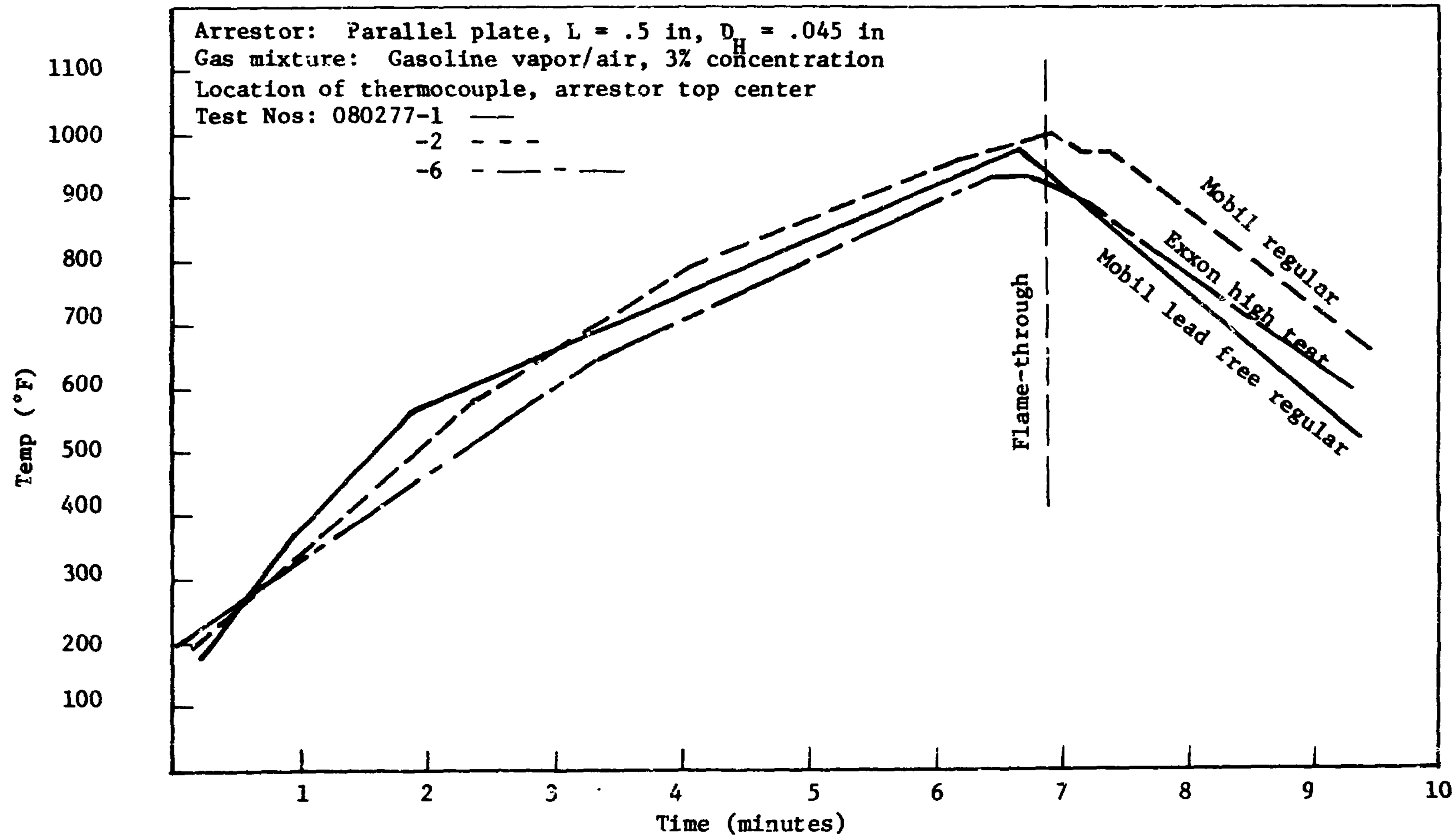


Figure 11: Thermocouple History During Heat-Up

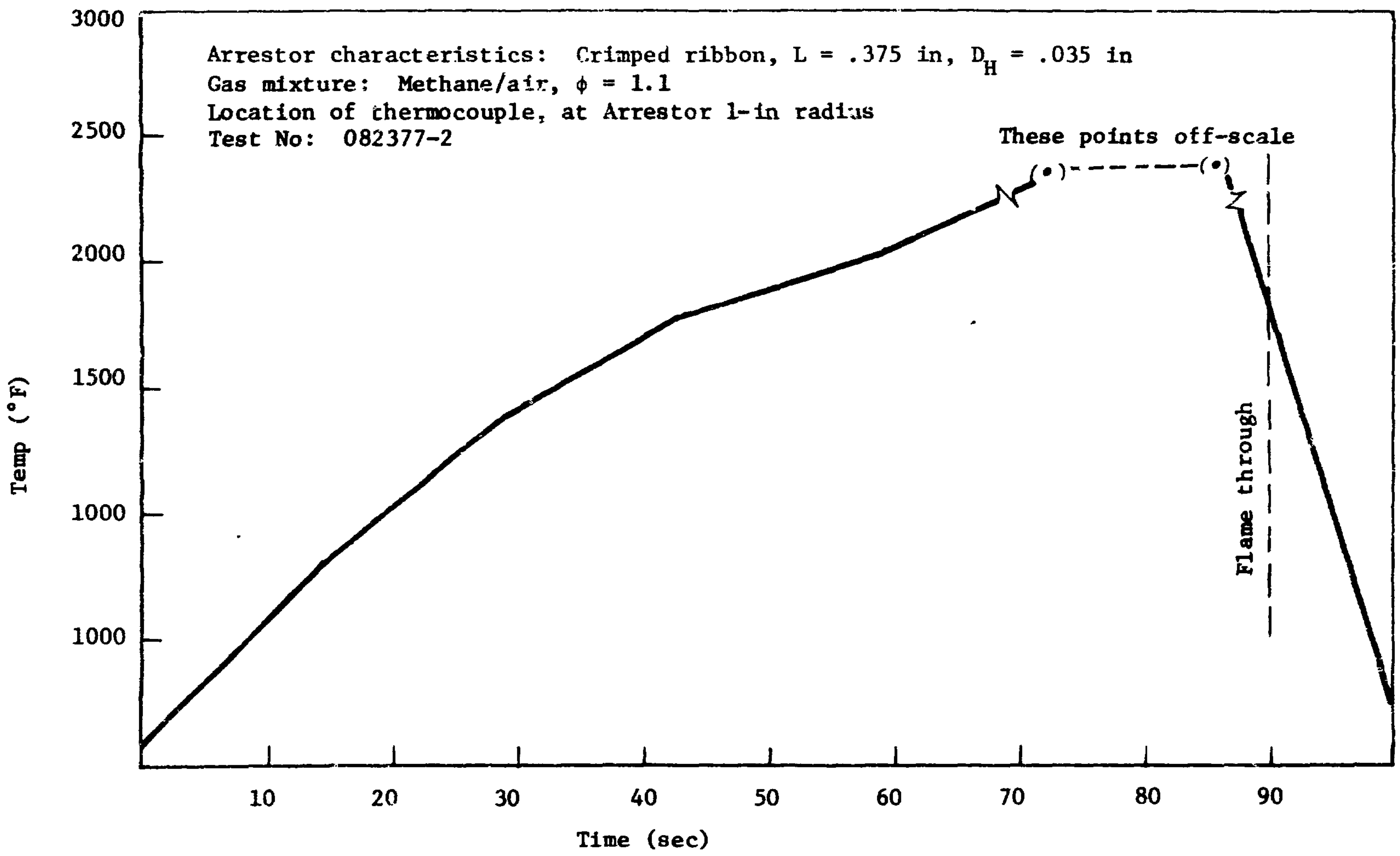


Figure 12: Crimped Ribbon Arrestor Temperature History During Heat-Up

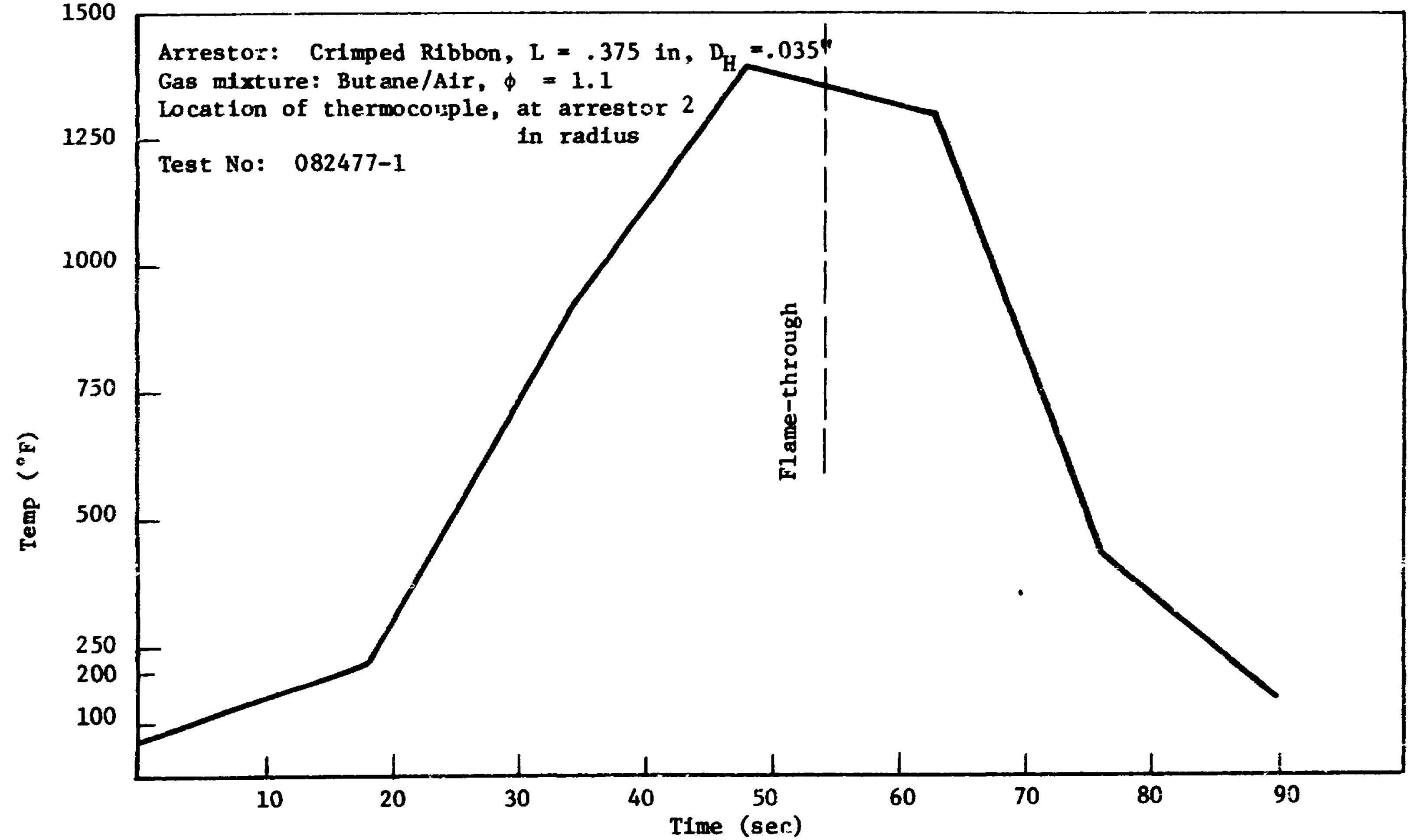


Figure 13: Arrestor Temperature History During Heat-Up

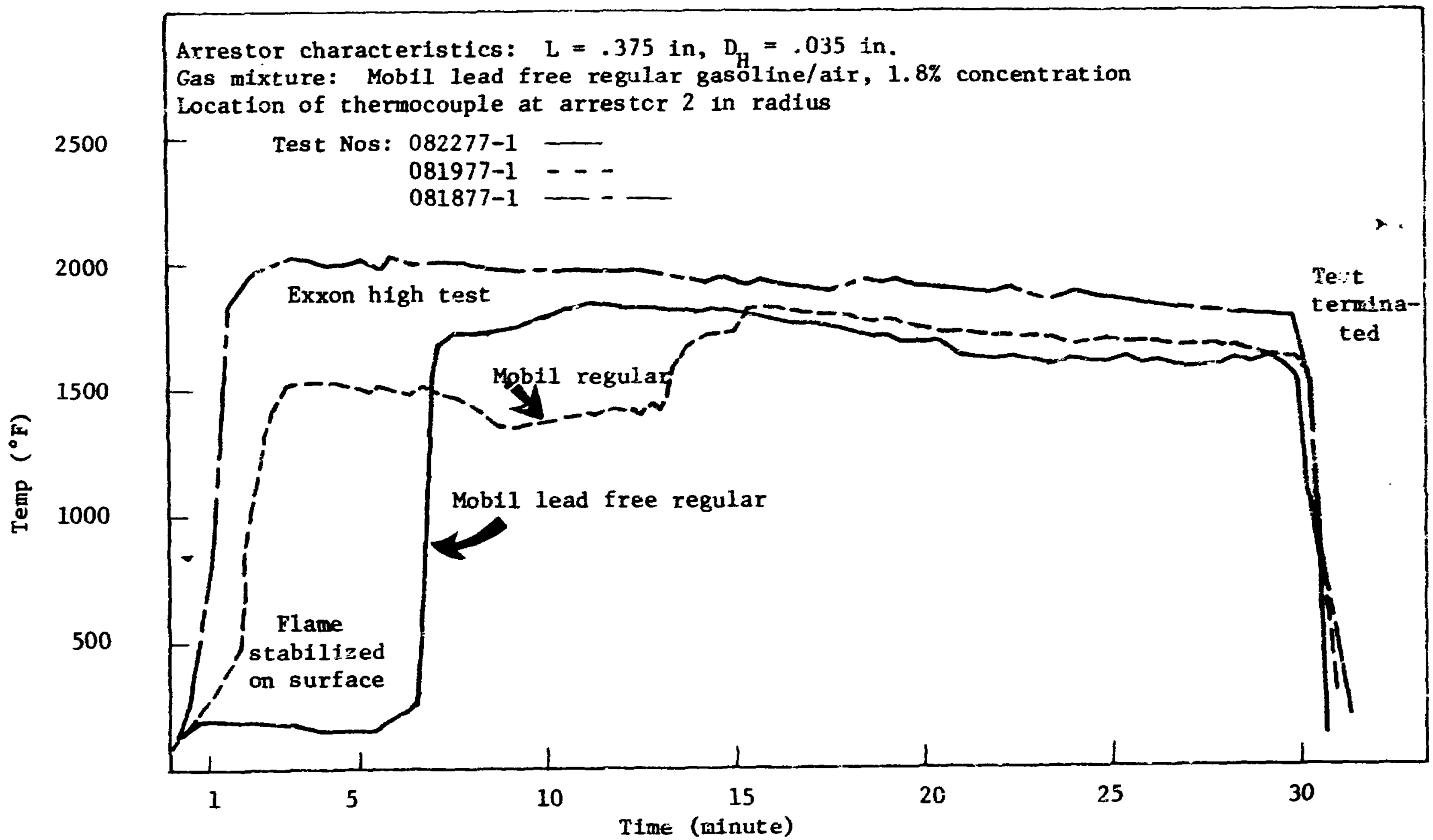


Figure 14: Crimped Ribbon Arrestor Temperature History During Heat-Up

This suggests that the flames during the tests were concentrated in the center section of the crimped ribbon arrestor. Maximum temperatures at the top of the arrestor also indicate this effect; i.e., thermocouple No. 3 (located at 3" radially from the arrestor center) was generally cooler than the other two thermocouples (see Table A-1, Appendix A). The localized flame effect was not visually obvious for the parallel plate arrestor presumably because of the generally lower maximum temperatures of the arrestor and the higher thermal conductivity. However, thermocouple No. 2 (located in the top center of the arrestor) indicated generally higher temperatures than the other two top thermocouples (see Table A-1, Appendix A).

Since a 6 mesh, .030" dia. wire screen used to help support the top of the crimped ribbon arrestors during the tests, heat-up tests were performed to determine if the screen effected the arrestor performance, using gasoline/air mixtures (3% concentration).

The results of the tests are tabulated in Table 5 and are plotted in Figure 15. The results show that although in the test with the screen the arrestor exhibited a slight heating delay, overall performance of both arrestors are similar. That is, thermal stability was reached in each arrestor (differences in maximum temperature were within normal variances) and both successfully controlled the flames for 30 minutes.

B. Conclusions

1. The parallel plate arrestor, whose dimensions ($L = 0.5$", $D_H = .045$") had been shown to be marginal for arresting moving flames (e.g., will arrest low speed flames but not high speed flames) did not control stabilized flames during heat-up test using butane/air or gasoline vapor/air for periods longer than approximately one to ten minutes. However, it controlled methane/air flames for periods averaging 25 minutes.

Table 5

Results of Tests to Determine the Effect of 6 Mesh, .030" dia. Wire Screen on Arrestor Performance

Arrestor: Crimped Ribbon, L = .375", D_H = .035"

Gas Mixture: Exxon High Test, 3% concentration

Test Conditions: Downstream ignition, no orifice, mixture velocity approximately 2 ft/sec, run up length 68-1/2"

Test No.	Test with Screen: Time (min)	Top Temp (°F)	Bottom Temp (°F)	Test No.	Test without Screen: Time (min)	Top Temp (°F)	Bottom Temp (°F)
083177-1	0	66	66	090177-2	0	88	88
	3	169	-		1	165	-
	6	204	-		1.4	1050	-
	6.5	208	121		2	1360	-
	7.0	690	-		3	1730	370
	8	1630	870		4	1750	
	10	1800	1020		5	-	640
	15	1910	1050		8	1810	-
	20	1900	1040		10	1780	780
	25	1880	1020		15	1735	780
	30	1830	950		20	1740	800
					25	1740	800
					30	1740	800

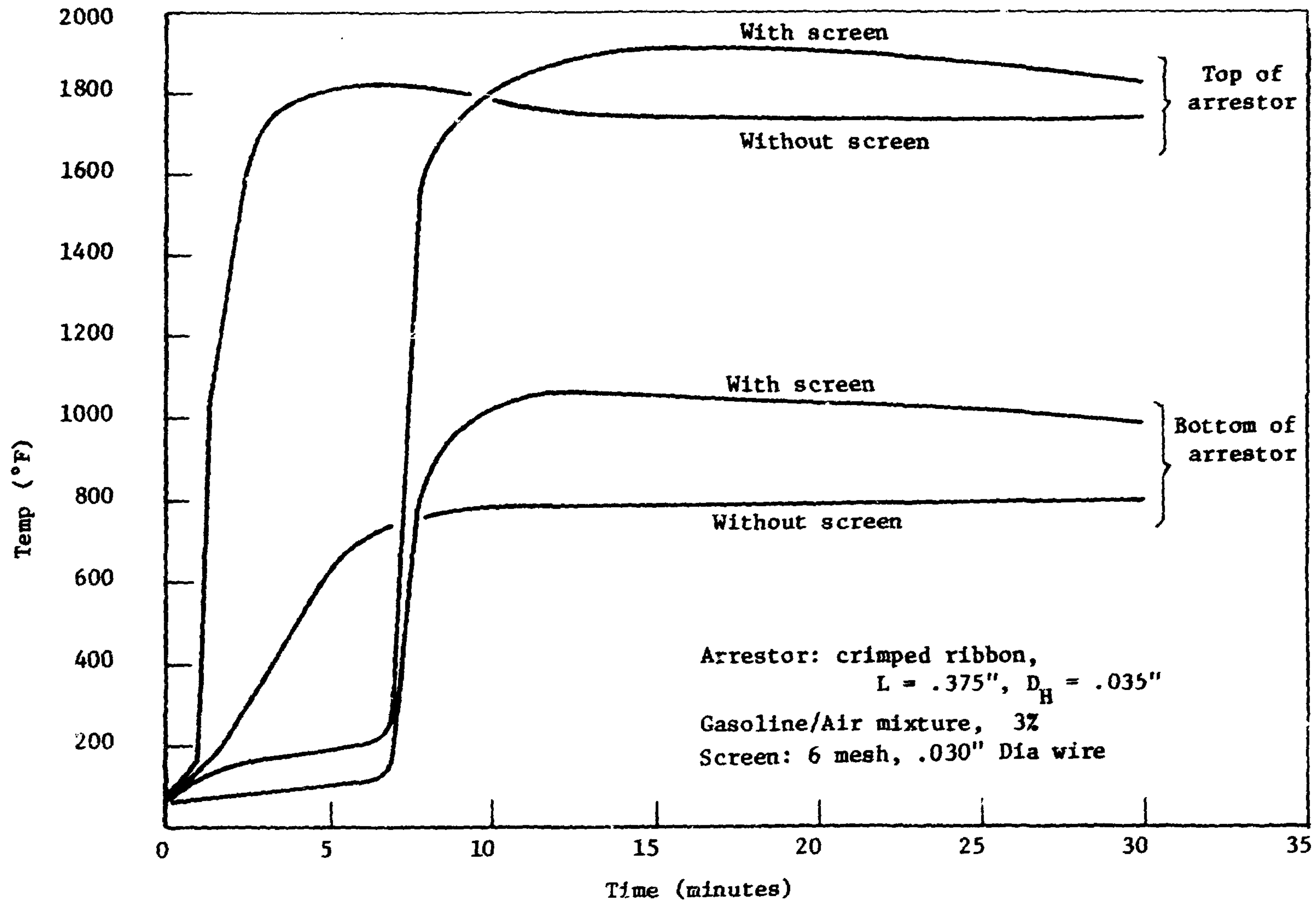


Figure 15: Effect of Screen on Arrestor Performance During Heat-Up Tests.

2. The crimped ribbon arrestor, whose dimensions (L = .375", D_H = .031") had been shown to be marginal for arresting moving methane/air and butane/air flames, failed to control stabilized flames from those same mixtures for periods longer than approximately one to three minutes on the average. However, it successfully controlled flames from gasoline vapor/air for periods of 30 minutes.

3. Based on findings 1 and 2, the design criteria (maximum D_H) to withstand prolonged exposure to a stabilized flame are more stringent than the criteria for quenching or stopping a moving flame. However, the reduction in D_H required for a stabilized flame below that required for a transient flame does not appear to be large.

4. Thermal equilibration occurred for the parallel plate arrestor and crimped ribbon arrestor in 7 minutes and 1 minute, respectively; this response time of course depends on thermal properties (conductivity, heat capacity, thickness of elements, depth of arrestor, etc.). In practical situations, the arrestor heat-up time will be available for mixture shut-off, dilution, steam snuffing or other corrective measures. Therefore the arrestor must be designed to keep the metal temperature in the bottom layer of the arrestor below critical levels as long as possible.

5. Flame passage occurred at the following values of arrestor metal temperature at the center-bottom of the arrestor: 770 ± 170°F for methane/air, 730 ± 100°F for gasoline vapor/air, and 460 ± 40°F for butane/air.

APPENDIX A

DETAILED RESULTS OF HEAT-UP TESTS

Table A-1

Arrestor Heat-Up Test Results

Test Number	ARRESTOR CHARACTERISTICS Type	D_H (in)	L (in)	MIXTURE CHARACTERISTICS Fuel	ϕ	Mix Speed (ft/sec)	IGNITION Run-up (in)	Orifice Dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	V_{34} $(\frac{ft}{sec})$	Y	N**	Time To Flame Through
072877-4	Parallel Plate	.045	.5	Butane	1.1	5	68½	None	8.0	6.2	X		1.05
-5	Parallel Plate	.045	.5	Butane	1.1	6	68½	None	7.1	7.8	X		1.4
-6	Parallel Plate	.045	.5	Butane	1.1	4	68½	None	9.1	6.9	X		2.5
-8	Parallel Plate	.045	.5	Butane	1.1	3	68½	None	5.7	5.7	X		1.0
-10	Parallel Plate	.045	.5	Butane	1.1	3	68½	None	5.6	6.2	X		.8
-11	Parallel Plate	.045	.5	Butane	1.1	3	68½	None	3.6	5.4	X		.73
080177-1	Parallel Plate	.045	.5	Gasoline Mobil Lead Free Regular ("GMLFR")	3%	2	68½	None	2.0	.6	X		12.2
-2	Parallel Plate	.045	.5	GMLFR	3%	2	68½	None	2.1	.8	X		7.2
080277-1	Parallel Plate	.045	.5	GMLFR	3%	2	68½	None	-	-	X		6.9
-2	Parallel Plate	.045	.5	GMLFR	2%	2	65½	None	2.3	2.3	X		6.1
-3	Parallel Plate	.045	.5	GMLFR	2%	2	68½	None	2.9	1.6	X		5.9
080377-1	Parallel Plate	.045	.5	Gasoline Mobil Regular ("GMR")	3%	2	68½	None	1.0	1.2	X		9.4
-2	Parallel Plate	.045	.5	GMR	2%	2	68½	None	2.1	.6	X		7.4
-3	Parallel Plate	.045	.5	GMR	3%	2	68½	None	.3	.8	X		6.5
-4	Parallel Plate	.045	.5	Gasoline Exxon High Test	3%	2	68½	None	.1	1.1	X		9.6
-5	Parallel Plate	.045	.5	GEHT	2%	2	68½	None	2.8	1.7	X		11.6
-6	Parallel Plate	.045	.5	GEHT	3%	2	68½	None	.9	1.3	X		6.9

Table A-1

Arrestor Heat-Up Test Results

Test Number	TEMPERATURE-AT-FLAME-THROUGH*** ARRESTOR TOP			ARRESTOR MIDDLE			ARRESTOR BOTTOM		
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_9
072877-4	404	554	418	413	413	-	458	386	313
-5	390	546	386	375	375	-	418	369	305
-6	418	585	416	412	462	-	427	440	352
-8	342	511	350	345	386	-	341	187	199
-10	449	504		422	-	-	440	-	365
-11	238	300	233	231	-	230	245	183	197
080177-1	705	952	701	671	-	620	744	723	589
-2	730	969	730	701	-	650	641	791	641
080277-1	727	977	701	757	-	753	615	765	628
-2	748	1002	756	723	-	637	635	748	633
-3	753	1015	765	723	-	637	635	748	637
080377-1	731	977	744	710	753	740	782	530	533
-2	756	1003	740	-	787	769	807	771	-
-3	744	956	727	-	757	757	778	576	-
-4	696	952	-	-	740	739	736	-	524
-5	765	1024	705	-	842	658	842	-	585
-6	740	939	753	-	791	770	791	-	615

Table A-1

Arrestor Heat-Up Test Results

Test Number	Arrestor Characteristics: Type	D_H (in)	L (in)	Mixture Characteristics: Fuel	ϕ	Mix Speed (ft/sec)	Ignition: Run-up (in)	Orifice Dia. (in)	Results: V_{23}^{*} ($\frac{ft}{sec}$)	V_{34} ($\frac{ft}{sec}$)	Y	N**	Time To Flame Through
080477-2	Parallel Plate	.045	.5	Methane	1.1	4	68½	None	7.1	7.4		X	>11.5
-3	Parallel Plate	.045	.5	Methane	1.1	4	68½	None	4.8	1.5	X		26.4
-4	Parallel Plate	.045	.5	Methane	1.1	5	68½	None	6.4	5.4	X		29.3
-5	Parallel Plate	.045	.5	Methane	1.1	5	68½	None	6.1	4.2	X		16.1
080577-1	Parallel Plate	.045	.5	Methane	1.1	5	68½	None	3.5	4.3	X		21.7
080677-1	Parallel Plate	.045	.5	Methane	1.1	5	68½	None	4.9	3.4		X	30.3
081777-1	Crimped Ribbon	.035	.375	Gasoline Exxon Hi Test	2.2%	2	68½	None	1.2	.5		X	-
-2	Crimped Ribbon	.035	.375	GEHT	2.1%	2	68½	None	-	1.3		X	-
081877-1	Crimped Ribbon	.035	.375	GEHT	1.7%	2	68½	None	2.6	1.8		X	-
-2	Crimped Ribbon	.035	.375	Mobil Regular	2.2%	2	68½	None	2.0	2.2		X	-
-3	Crimped Ribbon	.035	.375	MR	2.4%	2	68½	None	2.0	1.4		X	-
081977-1	Crimped Ribbon	.035	.375	MR	1.9%	2	68½	None	2.4	2.8		X	-
-2	Crimped Ribbon	.035	.375	Mobil Regular Lead Free	2.6%	2	68½	None	.5	.4		X	-
-3	Crimped Ribbon	.035	.375	MRLF	2.3%	2	68½	None	2.3	1.7		X	-
082277-1	Crimped Ribbon	.035	.375	MRLF	1.8%	2	68½	None	2.4	1.2		X	-
-2	Crimped Ribbon	.035	.375	Methane	1.1	5	68½	None	4.3	5.4	X		-
-3	Crimped Ribbon	.035	.375	Methane	1.1	5	68½	None	5.3	7.8	X		7.0
082377-1	Crimped Ribbon	.035	.375	Methane	1.1	5	68½	None	3.8	5.4	X		1.5
-2	Crimped Ribbon	.035	.375	Methane	1.1	5	68½	None	7.1	7.4	X		1.5
082477-2	Crimped Ribbon	.035	.375	Methane	1.1	5	68½	None	4.2	6.9	X		1.9

Table A-1

Arrestor Heat-Up Test Results

Test Number	ARRESTOR TOP			TEMPERATURE-AT-FLAME-THROUGH*** ARRESTOR MIDDLE			ARRESTOR BOTTOM		
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_9
080477-2	977	1131	927	-	927	882	882	-	646
-3	1108	1235	1101	-	1032	1032	973	-	871
-4	1163	1219	1159	-	1036	1036	960	-	872
-5	1150	1304	1134	-	1041	1041	956	-	829
080577-1	1108	1287	1112	-	1036	1024	931	-	804
080877-1	1166	1291	1162	-	1054	993	977	-	871
081777-1	1319	1664	1382				703	810	212
-2	1223	1549	1425				693	225	585
081877-1	1811	2035	1866				888	364	848
-2	1142	1531	379				790	576	413
-3	1099	1362	1099				751	628	471
081977-1	1473	1836	1000				970	874	453
-2	1123	1364	1080				788	498	329
-3	1172	1401	1053				985	458	578
082277-1	1694	1807	841				958	769	143
-2	2250	2250	563				628	409	467
-3	1642	2210	748				352	143	274
082377-1	2186	2098	-				493	493	100
-2	2250	2250	418				563	520	-
082477-2	-	2250	1159				956	914	884

Table A-1

Arrestor Heat-Up Test Results

Test Number	ARRESTOR CHARACTERISTICS			MIXTURE CHARACTERISTICS			IGNITION		RESULTS				
	Type	D_H (in)	L (in)	Fuel	ϕ	Mix Speed (ft/sec)	Run-up (in)	Orifice Dia. (in)	V_{23}^{*} $(\frac{ft}{sec})$	V_{34} $(\frac{ft}{sec})$	Y	N^{**}	Time To Flame Through
082377-3	Crimped Ribbon	.035	.375	Butane	1.1	5	68½	None	7.1	10.4	X		.9
-4	Crimped Ribbon	.035	.375	Butane	1.1	5	68½	None	6.2	4.6	X		1.1
-5	Crimped Ribbon	.035	.375	Butane	1.1	5	68½	None	8.3	12.5	X		1.0
082477-1	Crimped Ribbon	.035	.375	Butane	1.1	5	68½	None	5.7	9.6	X		.9

Table A-1

Arrestor Heat-Up Test Results

Test Number	ARRESTOR TOP			TEMPERATURE-AT-FLAME-THROUGH*** ARRESTOR MIDDLE			ARRESTOR BOTTOM		
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_9
082377-3	2195	[illegible]	1057				485	391	169
-4		[illegible]	812				572	314	319
-5		1403	693				449	413	195
082477-1	804	1398	723				520	563	493

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the top face of the arrestor, respectively.

V_{34} is the average flame speed between points 3 and 4 located 17" and 2" from the top face of the arrestor, respectively.

**N denotes no flame-through after 30 minutes fire exposure.

***If no flame-through occurred, temperatures given are maximum during the 30 minute exposure.

APPENDIX B

DETERMINATION OF GASOLINE VAPOR COMPOSITION VARIATION WITH TIME

Gas samples were taken from the outlet of the gasoline vapor converter at various time intervals over the 30 minute operation of the converter. The samples, obtained using a flow-through extraction method, were subsequently analyzed using standard gas chromatography (GC) procedures. Converter operating conditions during the test were similar to that during normal operation for arrestor heat-up tests; that is, gasoline temperature 120°F, gasoline circulation rate 275 ml/min, nitrogen gas temperature and flow rate 120°F and 3.5 CFM, respectively. During the test, the vaporization rate was approximately 40 gm/min average over the 30 minute period. (In prior tests over a 5 minute period, the vaporization rate was greater by about a factor of four because of high volatiles evolved in the early phases--see reference 3.)

Gas vapor samples were taken at intervals of 1, 3, 10 and 30 minutes during the test. Analysis of the liquid gasoline was made before and after the test. The gasoline tested was Exxon High Test.

Results

Table B-1 lists the results of the GC analyses of both liquid and gasoline vapor samples taken before, during and after the test. Based on the tabulated data, the gasoline vapor composition variation with time is plotted in Figure B-1. The data in the figure illustrates that during the first 10 minutes of the converter operation, a high fraction (approximately 65%) of low boiling components was generated and diminished to a more stable lower level (approximately 35%); whereas the concentration of high boilers such as tri & tetramethylbenzene, and xylenes increased from zero to more stable levels ranging

Table B-1

	Lower Boiling than Toluene **	Toluene* $C_6H_5CH_3$	Xylenes	Trimethyl Benzenes	Tetramethyl Benzenes and Higher Boiling
Starting Gasoline	25.7%	20.3%	16.5%	19.8%	17.7%
Sample Vapor at 1 min	63.5%	28.7%	6.2%	1.6%	-
Sample Vapor at 3 min	47.6%	34.5%	10.6%	5.6%	1.6%
Sample Vapor at 10 min	35.4%	27.5%	15.5%	14.5%	7.2%
Sample Vapor at 30 min	37.5%	29.2%	14.8%	12.7%	5.9%
"Final Gasoline at 30 min	28.4%	21.8%	15.6%	18.2%	16.0%

*GCMS saturated on Toluene in the vapor samples. It was the largest single component.

**Boiling point 233°F or less.

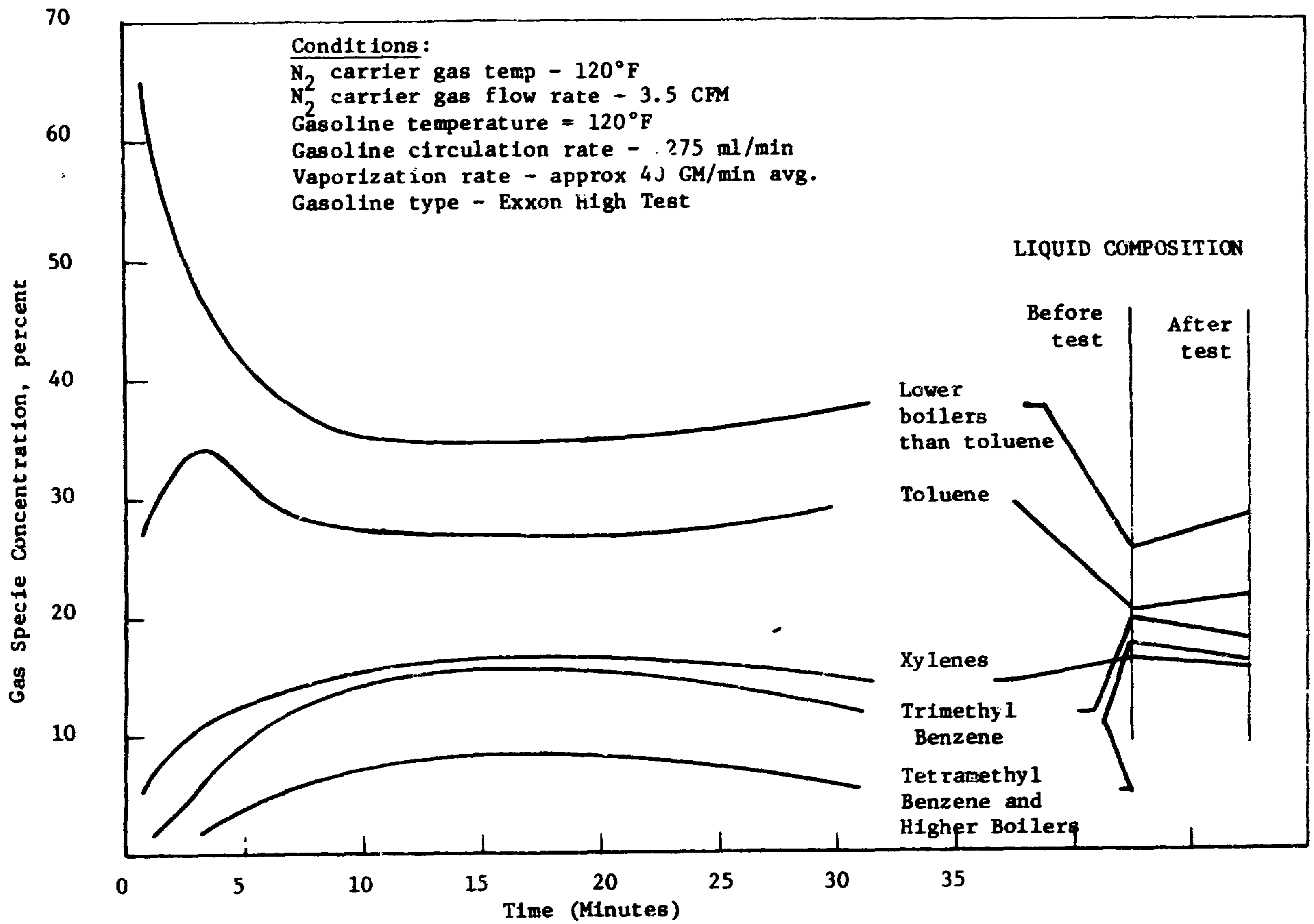


Figure B-1: Gasoline Vapor Composition History During Operation of Gasoline Vapor Converter.

between 6 and 16 percent. Following an initial surge in concentration, toluene remained more or less stable at approximately 28% for most of the test period.

The lack of significant change in composition of the liquid gasoline extracted before and after the tests was due to the replenishing effect of continuous circulation of gasoline which is a normal part of the converter operation.

REFERENCES

1. Bolta, C., Friedman, R., Griner, G., Markels, M., Tobriner, M., and Von Elbe, G., "Lightning Protection Measures for Aircraft Fuel Systems (Phase II)," FAA ADS-18, Atlantic Research Corp., (1964).

2. Rogowski, Z. and Ames, S., "Performance of Metal Foam as a Flame Arrestor when Fitted to Gas-Explosion-Relief Vents," Fire Research Note No. 931, Fire Research Station (Herts, England), 1973.

3. Wilson, R. P. and Crowley, D. P., Preliminary Draft, "Performance of Commercially Available Flame Arrestors for Butane/Air and Gasoline/Air Mixtures," DOT-CG-42357A, ADL 77396-13-14, Office of Research and Development, USCG, 400 Seventh Street, S.W., Washington, D.C. 20590, June 1977.

4. Wilson, R. P. and Atallah, S., "Design Criteria for Flame Control Devices for Cargo Venting Systems," Report No. CG-D-157, Office of Research and Development, USCG, Washington, D.C. 20590, August 1975.